Final project report for grant number 104141

Title: Thermal transport in 1-D and 2-D nanostructures

Principal Investigator: Mandar M. Deshmukh

Proposed objectives:

The key goals of our proposed work is

- Probe thermal conductivity of 1D and 2D nanostructures with structured defects
- Understand the role of phonon scattering at interfaces and surfaces
- Explore the thermal transport in NEMS devices while they are resonating
- Study the relative thermal conductivity of phonons and electrons

Number of resulting publications – three (1PRB, 2 APL).

Report Documentation Page

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14. ABSTRACT
We have measured the thermal conductivity of individual nanowires with engineered defects. The key emphasis is on studying how the phonon spectrum can be modified using defect engineering in 1D and 2D systems. Our work with nanowires suggests that strong localization of phonons is possible due to twin defects oriented perpendicular to the axis of nanowires. This results in the reduction of measured thermal conductivity by three orders of magnitude. As a result of the significant reduction in thermal conductivity the phonon contribution to thermal conductivity becomes comparable to the electronic contribution. A significant fraction of the electronic contribution to thermal conductivity can be tuned by an electrostatic gate ?- a realization of a thermal field effect transistor and analogue of the electrical FET.

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thermal transport , nano materials, nano structures

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* **Thermal transport in individual nanowires**

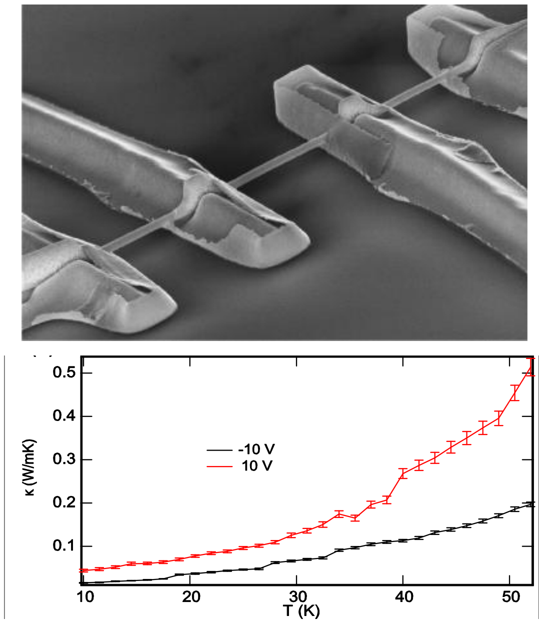

Figure 1 (upper panel) SEM image of a four probe suspended nanowire device device use to measure thermal conductivity of individual nanowire using the 3ω technique. The total length of the nanowire is 12 μm. (lower panel) Thermal conductivity measured using as a function of the gate voltage that tunes the density of electrons.

Understanding thermal transport at nanoscale is crucial to developing new semiconducting technologies and for developing design rules for next generation thermoelectric architecture. We have measured the thermal conductivity of individual nanowires with engineered defects. The key emphasis is on studying how the phonon spectrum can be modified using defect engineering in 1D and 2D systems. Our work with nanowires suggests that strong localization of phonons is possible due to twin defects oriented perpendicular to the axis of nanowires. This results in the reduction of measured thermal conductivity by three orders of magnitude. As a result of the significant reduction in thermal conductivity the phonon contribution to thermal conductivity becomes comparable to the electronic contribution. A significant fraction of the electronic contribution to thermal conductivity can be tuned by an electrostatic gate -- a realization of a thermal field effect transistor and analogue of the electrical FET.

Key results of our work:

* Twin crystal defects and the resulting interfaces provide key thermal impedance
* Contribution of phonons to thermal conductivity can be reduced to the level of electronic contribution
* Electronic contribution is tunable by tuning the density of electrons using a gate electrode

- **Probing field effect modulation across metal-insulator transition**

This work does not directly connect to thermal transport but looks at a very interesting aspect of metal insulator transitions by probing their electrical properties. Future measurement on this system across the metal to insulator transition would be helpful in discerning the exact contribution of electrons to thermal conductivity and also look at the thermoelectric properties.

VO_2 undergoes an insulator-to-metal transition accompanied by a change in its crystal structure, the mechanism of which is still under debate. The transition temperature of a free crystal is 341 K. Its proximity to room temperature has motivated attempts at fabricating Mott field-effect transistors (FETs) to induce the phase transition by applying a gate voltage. Such experiments have so far been conducted on thin films of VO_2. Recently it has been realized that single-crystalline VO2 nanobeams support single or ordered metal-insulator domains during the phase transition. This eliminates the random, percolative domain structures occurring in thin films, and allows intrinsic transition physics to be probed. We have extensively studied electrostatic gating measurements on single crystalline VO_2 beams using HfO_2 as the gate dielectric. The devices have a hysteretic response and appear to possess a memory persisting over a large timescale (a few minutes). The field effect studies have been done at different temperatures in the insulating and metallic phases

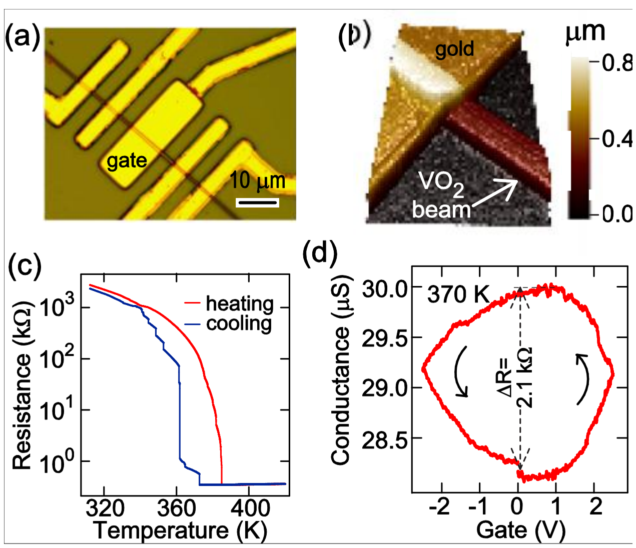

Figure 2 (a) Optical microscope image of a VO_2 device. (b) Atomic force microscope image of a VO_2 device. (c) Resistance (in logscale) as a function of temperature for Device 1. The steps in the cooling curve indicate metal–to insulator transition of individual domains. (d) Conductance of VO_2 as a function of gate voltage. This hysteretic response is similar to the memristive response.

of the system. Our study is interesting as it shows memristor like response in a FET made using VO_2. In the past decade there has been a renewed interest in memristive devices as potential storage devices.

Key results of our work:

- It is possible to modulate the conductance across a metal insulator transition

- **Electromechanics using InAs nanowires at low temperature**

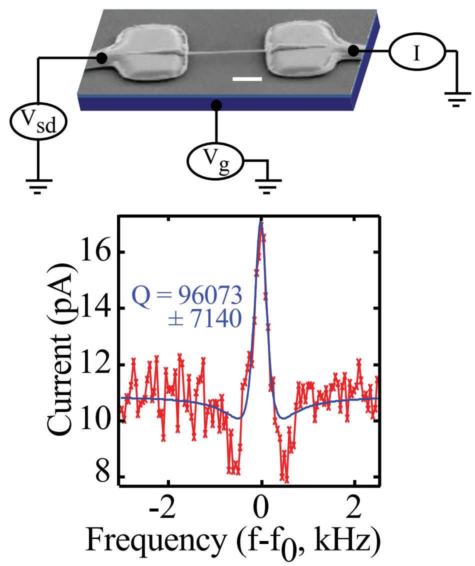

Figure 3 (upper image) Tilted SEM image of nanowire resonator. (lower image) Resonance curve showing high quality factor ~ 100000 at 100mK. The resonant frequency of the resonator is 53.6838 MHz.

Out experiments with InAs nanowires have shown that high Q electromechanics is possible with this system. Combining these ideas we expect to combine these two ideas to explore coupling of spin and mechanical degrees of freedom. In addition exploring the charge physics with double quantum dots embedded in semiconducting nanowires is possible and will result in new and interesting physics.

We next intend to use this structure of devices to study thermal transport at low temperatures and this should allow us to further investigate the interplay between motion and thermal transport.

Key results of our work:

- High Q achievable in nanowire resonator allowing the future work to study the thermal transport in NEMS structures

<u>Publications related to the project and AOARD funding has been acknowledged</u>

1. *Tunable thermal conductivity in defect engineered nanowires at low temperatures*

Sajal Dhara, Hari S. Solanki, Arvind Pawan R., Vibhor Singh, Shamashis Sengupta, B.A. Chalke, Abhishek Dhar, Mahesh Gokhale, Arnab Bhattacharya, and **Mandar M. Deshmukh**
*Physical Review B **84**, 121307(R) (2011).*

2. *Field-effect modulation of conductance in VO_2 nanobeam transistors with HfO_2 as the gate dielectric*
   Shamashis Sengupta, Kevin Wang, Kai Liu, Ajay K. Bhat, Sajal Dhara, Junqiao Wu, **Mandar M. Deshmukh**
   *App. Phys. Lett. **99**, 062114 (2011).*

3. *High-Q electromechanics with InAs nanowire quantum dots*
   Hari S. Solanki, Shamashis Sengupta, Sudipta Dubey, Vibhor Singh, Sajal Dhara, Anil Kumar, Arnab Bhattacharya, S. Ramakrishnan, Aashish A. Clerk and **Mandar M. Deshmukh**
   accepted in Applied Physics Letters (in press); http://arxiv.org/abs/1108.3255)